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Title: Muscle activation in world champions, world-class and national breaststroke swimmers

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Abstract

Purpose: Investigating the muscle activation patterns and coactivation with the support of kinematics in some of the world's best breaststrokers and identify performance discriminates related to national elites at maximal effort. ***Methods:*** Surface electromyography was collected in eight muscles from four world-class (including two world champions) and four national elite breaststroke swimmers during a 25 m of breaststroke at maximal effort. ***Results:*** World-class spent less time during the leg recovery (p = .043), began this phase with a smaller knee angle (154.6° vs 161.8°) and had a higher median velocity of 0.18 m/s during the leg glide compared to national elites. Compared to national elites, world-class swimmers showed a difference in the muscular activation patterns for all eight muscles. In leg propulsion phase; less triceps brachii activation (one swimmer 6% vs median 23.0% (8.8)). In leg glide phase; activation in rectus femoris and gastrocnemius during the beginning of this phase (all world-class vs only one national elite), a longer activation in pectoralis major (world champions 71% (0.5) vs 50.0 (4.3)) (propulsive phase of the arms). In leg recovery phase; more activation in biceps femoris (50.0% (15.0) vs 20.0% (14.0)), and a later and quicker activation in tibialis anterior (40.0% (7.8) vs 52.0% (6.0)). In the stroke cycle; no coactivation in tibialis anterior and gastrocnemius for world champions. ***Conclusion:*** These components are important performance discriminants. They can be used for improving muscular activation patterns and kinematics through the different breaststroke phases. Further, they can also be used as focus points for learning breaststroke to beginners.

Keywords: swimming, electromyography, coactivation, motion analysis, performance

Introduction

Only a few athletes become world champions while others remain at the national elite (NE) level. In breaststroke swimming, as in most other activities with an endurance component, athletes reaching the highest level show the highest mean velocity throughout the competition. The velocity changes within a breaststroke cycle and kinematical variables can identify this through breaking the stroke into for example smaller phases and angles of the limbs. To reach the highest mean velocity several factors play an important role, including anthropometrics,[1] strength,[2] flexibility,[3] swimming economy[4] and psychology.[5] In addition, swimming technique and race tactics play an important role in the performance outcome[6] together with muscular activation.[7,8] Many of the factors that are required for performing at the world-class (WC) level are well documented,[9,10] but only very limited knowledge is available that quantifies how muscles are coordinated and coactivated, and/or the level of activation, especially in contemporary breaststroke swimming. Most of the research that has been conducted in swimming is limited to front crawl and the earlier style of breaststroke.[11] Contemporary breaststroke permits the swimmer to go beneath the water surface with the head during parts of the stroke cycle, recover the arms and hands at or above the water surface, incorporates different degrees of body undulations throughout the stroke cycle and characterized by a deeper leg extension.[12]

The first study comparing the muscle activation patterns from WC swimmers to other performance levels had some methodological challenges, the absence of normalization and identification of stroke phases made it hard to compare the groups.[13] Later,[14] found that Olympic swimmers showed longer activation of the tibialis anterior and better timing with the use of gastrocnemius. This allowed for a longer dorsiflexion of the foot, resulting in a more effective kick, than members of a University swimming club and average adults. In the best swimmer, activity of the rectus femoris was observed during the first part of gliding, showing that full extension of the knee joint occurred after the feet were almost together. The Olympic swimmer also showed higher and earlier activity in the biceps brachii (long head) during the pull-phase to perform the elbow-up pull with earlier elbow flexion to achieve large propulsion. A study of the lower-limb flexion-extension in the contemporary breaststroke,[15] found different muscle activation among international and national level swimmers to produce similar movements. They found that the international level swimmer was the only one to maintain muscle activity during the gliding phase to actively reach a better streamlining position to limit drag increase.

Measuring muscle activation with surface electromyography (EMG) make it possible to observe an expression of the dynamic involvement of specific muscles in the propulsion of the body through the water.[16] Such information is important for a better understanding regarding the coordination, coactivation and intensity of activity in muscles and their relative contribution to overall propulsion. Coactivation between muscles is also generally involved in the processes of determining movement efficiency, safety, control of the precision and velocity of movement, and for stabilizing single joints.[17] While coactivation is necessary during certain movements,[18] excessive activation in antagonist muscles is associated with increased metabolic costs and an inefficient use of energy,[19] which could lead to an earlier onset of fatigue and be detrimental to performance.

To find the optimal muscle activation pattern it is necessary to assess it in the world's best swimmers. It is therefore equally important to know whether there are differences between swimmers at different performance levels that can be identified as performance discriminators. Such knowledge is also important to provide coaches and swimmers with the most relevant key points for these variables. It can be used not only for improving training efficiency and technique in swimmers who wish to reach the highest level, but also for teaching breaststroke to beginners, designing applicable weight training and establishing dry-land programs. The purpose of this study was therefore to investigate the muscle activation patterns and coactivation with the support of kinematics in some of the world's best breaststrokers and identify performance discriminates related to national elites (NEs) at maximal effort. We hypothesized that WC swimmers would have a shorter time in the different phases and show more effective muscle activation patterns than NEs.

Methods

Participants

Four WC breaststroke swimmers (medallists at international championships) including two male world champions and four NE (medallists at national championships) participated in this study (Table 1). All participants signed an informed consent prior to the commencement of this study. The national ethics committee approved the study protocol and all procedures were in accordance with the Declaration of Helsinki.

******Table 1 near here******

Experimental protocol

All measurements were performed on the pool-deck and in a 25 m indoor swimming pool with air and water temperature of approximately 29 °C. Isometric maximal voluntary contractions (MVC) were performed for each muscle. The participants were instructed to exert a maximal isometric force and hold it for 5 s, separated by about 45 s of recovery in standardized exercises.[20] Each contraction was repeated three times. The joint angle during the MVCs was verified using a goniometer. After a 15 min personalised warm-up which included low to moderate intensity aerobic swimming and elements of kicking and drill exercises with the testing equipment, the swimmers performed 25 m breaststroke at maximal effort using in-water start. The maximal effort was measured through Borg's Rate of Perceived exertion and a score of 19 or 20 after completion was accepted as maximal effort.

Kinematic data collection

A 3D underwater motion-capture system with automatic motion tracking (Qualisys, Gothenburg, Sweden) consisting of six Oqus 4 cameras with sampling frequency of 100 Hz was used for collecting kinematical variables. The cameras had no exposure delay and the flash time was 4888 µs. Calibration was performed with an L-frame reference structure and a moving wand method[21] with two markers fixed with an inter-point distance of 749.5 mm following the recommendations of the manufacturer.[22] The wand was moved through the calibration volume at a slow pace to avoid wobbling of markers, and for a period of 300 s. The cameras covered a volume of approximately 37.5 m^3, 10 m (*X*; horizontally) x 2.5 m (*Y*; width) x 1.5 m (*Z*; vertically), and is presented in Figure 1.[23] The volume was calibrated in the middle of the pool (*Y*) starting one meter from the end of the swim (*X*). Qualisys Track Manager (QTM)® v2.8 (Qualisys, Gothenburg, Sweden) was used for the camera setup and capture.

******Figure 1 near here******

Passive, spherical markers with retro-reflective tape (Qualisys, Gothenburg, Sweden) developed to suit underwater usage (diameter 19 mm) were silicone embedded for fastening and had neutral buoyancy. They were attached to both sides of the swimmers' body on the following reference points: crista iliaca, trochanter major, lateral femoral condyle, most posterior part of calcaneus, medial and lateral malleolus, and 1st and 5th metatarsal.

Surface electromyographic data collection

Muscle activation was recorded telemetrically with surface EMG (Plux, Lisbon, Portugal) from eight muscles on the right side of the body: triceps brachii (lateral head), biceps brachii (long head), trapezius (pars descendens), pectoralis major (pars clavicularis), gastrocnemius medialis, tibialis anterior, biceps femoris (long head) and rectus femoris. Skin preparation procedures, electrode configurations and placements were performed using methods previously reported.[20] The EMG signals were acquired according to the recommendations from the International Society of Electrophysiology and Kinesiology[24] with band pass filter of 25-500 Hz (-6 dB), input impedance >100 MΩ, common mode rejection ratio of 110 dB, amplified with a gain of 1000 and sampled at 1 kHz.

Data processing

The pool was equipped with four digital underwater cameras Sony HDR-CX550VE Camcorder (Sony Corp., Tokyo, Japan). The cameras were placed inside a Sports pack waterproof cases, SPK-HCE (Sony Corp., Tokyo, Japan) for synchronisation of the EMG and 3D recordings and to verify the swimming movements in 2D. The Sony camera captured the first blink from the EMG equipment's reference light when EMG recording started. The EMG time log was then synchronized to the blinking onset/offset of the 3D cameras displayed in Figure 2.[23]

QTM v2.8 software was used to track and process the anatomical markers on the swimmers' body using a fit to 2nd degree curve filter.[25] Swim velocity, stroke length, phase time, stroke rate and knee angle for the complete stroke cycle and for each of the phases were measured. Based on the leg kick, each stroke cycle was divided in three phases: (1) leg propulsion: from the smallest knee angle during leg recovery until the first peak in knee angle (extension) during the leg propulsion, (2) leg glide: from end of the leg propulsion to the beginning of active knee flexion for leg recovery, and (3) leg recovery: from end of leg glide until the smallest knee angle. The leg kick was chosen for phase division due to its central role in generating propulsion.[26] In addition it provided reliable pictures of the movement since cameras where only placed underwater and markers on the upper body went out of the water during certain parts of the stroke cycle.

******Figure 2 near here******

The raw EMG signals were visually inspected to assure its quality using the MyoResearch XP Master Edition 1.08.32 (Noraxon, Scottsdale, AZ, USA), before further processing in Matlab R2012b (MathWorks, Natick, MA, USA). The raw EMG signals were processed according to the recommendations from the International Society of Electrophysiology and Kinesiology:[24] digitally filtered (20-500 Hz), full-wave rectified and smoothed with a low pass filter (12 Hz, 4th order Butterworth). Averaged EMG was calculated for each muscle during the stroke cycle. The EMG signals were amplitude normalised to the individual MVC. Because different phase timess were observed among the swimmers, each stroke phase was interpolated to 50 time points using Matlab R2012b. This allowed comparison between the swimmers with respect to muscle activation patterns within each phase.

For identifying muscular on- and offset, a threshold level of 20% of the peak EMG activation during the stroke cycle was selected for all muscles except for gastrocnemius, which showed a higher baseline activity and therefore the threshold level was set to 25%.[27] Coactivation was calculated as the time of agonist–antagonist activity above the threshold level divided by the time of the stroke cycle or phase for all muscle pairs.[17,28] Three to five stroke cycles within the calibrated volume were selected for further EMG and kinematic analyses.

Statistical analysis

IBM SPSS® Statistics v21.0 (IBM® Corporation, Armonk, NY, USA) were used for all statistical computations. Mann-Whitney tests were used for testing overall differences between the WC and NE swimmers kinematics for 16 variables. Significant at $p < 0.05$. Median values and the interquartile range (IQR) were used for presenting averaged EMG and co-activation from the 50 time points during each phase.

Results

Kinematics

WC spent less time during the leg recovery ($p = .043$). The largest difference in mean swimming velocity was found during the leg glide with WC being 0.13 m/s faster compared to NE. In addition WC started the leg recovery with a smaller knee angle than NE (154.6° vs 161.8°). Descriptive statistics of the kinematics are presented in Table 2a and 2b.

******Table 2a and 2b near here******

Electromyography

The individual muscle activation pattern remained constant throughout the seven stroke cycles and example for one NE swimmer’s triceps brachii activation is presented in Figure 3. An example of a world champion and NE swimmer regarding when the muscles were active during the stroke cycles is presented in Figure 4.

******Figure 3 near here******

******Figure 4 near here******

Triceps brachii (lateral head) and biceps brachii (long head)

The median activation for NEs in triceps brachii during the leg propulsion phase was 23.0% (8.8), while only one of the WCs showed activation beyond the threshold level (during the last 6.0%). Three of the NEs also showed activation beyond the threshold level in triceps brachii at the beginning of this phase. WCs activated biceps brachii at 53.0% (9.0) into the leg glide phase while NEs activated at 59.0% (3.0). In addition, one world champion activated the biceps brachii 30% into this phase.

The triceps brachii showed most individual patterns with two and three peaks during the stroke cycle for NEs while WCs only showed one (one world champion had two peaks). An example of the average triceps and biceps brachii muscle coordination through the stroke cycles from one NE and one world champion is presented in Figure 5A.

Gastrocnemius medialis and tibialis anterior

All of the swimmers started the leg propulsion phase with activation in tibialis anterior. NEs activated tibialis anterior for 87.0% (11.3) while WCs showed activation for 69.0% (12.0) of this phase. Only the two world champions and one NE showed activation in gastrocnemius at the end of this phase. The WCs showed activation in gastrocnemius at the beginning of the leg glide phase while only one NE had gastrocnemius activated. The NEs started activating tibialis anterior at 52.0% (6.0) into the leg recovery phase while WCs activated tibialis anterior for the last 40.0% (7.8). In addition two NEs showed coactivation between gastrocnemius and tibialis anterior for the last 38.0% of this phase. On the contrary to all other participants, the two world champions showed no coactivation between gastrocnemius and tibialis anterior during the whole stroke cycle. An example of the average muscle coordination through the stroke cycles from one NE and one world champion is presented in Figure 5B.

Biceps femoris (long head) and rectus femoris

Only one world champion started the leg propulsion phase with coactivation, but all of the swimmers showed coactivation between biceps and rectus femoris during this phase. While all of the WCs showed activation in rectus femoris during the beginning of the leg glide phase, only one NE showed activation in this muscle. WCs had biceps femoris activated for 50.0% (15.0) of the leg recovery phase while NEs showed activation for 20.0% (14.0). An example of the average muscle coordination through the stroke cycles from one NE and one world champion is presented in Figure 5C.

Trapezius (pars descendens) and pectoralis major (pars clavicularis)

Of the eight muscle groups tested, all swimmers showed the longest periods of activation for trapezius and pectoralis major relative to the stroke cycle. Six of the swimmers including both the world champions had trapezius activated throughout the leg propulsion phase. WCs had joined activation for 34.0% (10.0) of this phase, NEs for 12.0% (12.5), while one of the world champions for 80%. The world champions activated pectoralis major during 71% (0.5) of the leg glide phase while the other swimmers activated pectoralis major for 50.0 (4.3). An example of the average muscle coordination through the stroke cycles from one NE and one world champion is presented in Figure 5D.

******Figure 5 near here******

Discussion

The main aim of this study was to investigate performance discriminators in muscle activation patterns with the support of kinematical variables in WC and NE swimmers. WC swimmers showed different muscle activation patterns and coactivation for all of the eight muscles tested in this study compared to NEs, supporting the hypothesis of more effective muscle activation patterns in WC swimmers. In addition the WC subgroup of the two world champions sometimes showed different results than all the other swimmers. From the kinematical hypothesis, only the leg recovery phase showed a different result with WC swimmers spending less time compared to NEs. Therefore the kinematics will be discussed together with muscular activation patterns as supporting parameters.

Triceps brachii (lateral head) and biceps brachii (long head)

WC swimmers showed no activation in the triceps brachii during the leg propulsion phase (except for the last 6% in one swimmer). Three of the NEs showed activation at the beginning of this phase. This revealed that NEs started their leg propulsion phase before the upper body had reached the full streamlined position as was evident in the motion capture. In addition, the activation in triceps brachii in NEs during this phase indicated that they used triceps brachii during the streamline position of the upper body. This was in contrast to WCs who were able to rest this muscle and conserve energy during the non-propulsive arm phase.

WCs showed an earlier activation in biceps brachii into the leg glide phase than NEs, while one of the world champions activated even earlier into this phase, suggesting an even earlier elbow flexion and orientation of the propulsive surface.[14]

Gastrocnemius medialis and tibialis anterior

All swimmers started the leg propulsion phase with activation in tibialis anterior, demonstrating that they had dorsiflexion of the ankle at the beginning of this phase. The NEs showed a longer tibialis anterior activation than the WCs swimmers allowing a longer dorsiflexion of the foot. This was in contrast to previous findings where a longer tibialis anterior activation was found in Olympic swimmers.[14] The shorter tibialis anterior activation found in WCs could be explained by the evolution in breaststroke technique. Today's style is categorized by a deeper leg extension (towards the end of the leg propulsion phase) followed by a rising undulation of the feet during the insweep of the feet (at the beginning of the leg glide phase).[12] Motion capture from recent international championships also indicated that swimmers no longer use dorsiflexion at the end of the leg propulsion phase to create lift, but instead plantarflexion towards the end to ensure high feet velocities with less drag and a rising of the feet. Another explanation might be that the lift in this position does not contribute substantially to forward propulsion because of an already high forward velocity of the body. Further research is needed to confirm these phenomenon's and their contribution to lower drag or higher propulsion.

All WCs, but only one NE, showed activation in gastrocnemius at the beginning of the leg glide phase, suggesting that the WCs may be better at streamlining their ankles to reduce resistance during this phase.

Highly activated tibialis anterior at the beginning and during the leg recovery phase was found in Olympic swimmers.[29] By comparison, no swimmers in this study showed activation in tibialis anterior during the beginning of this phase. Therefore indicating that the breaststroke technique has changed and that today's style takes further advantage of the up-kick motion, with plantarflexion of the ankle to further reduce drag. This was also in accordance with the technique described in which the lower legs and feet recovered forward, and just before the feet reached the buttocks they were swept outwards and forward,[30] showing a contribution from tibialis anterior. NEs showed activation for tibialis anterior earlier in this phase compared to

WCs, revealing an earlier transition from plantarflexion to dorsiflexion of the ankle in NEs. This was evident in the motion capture, and therefore indicating that the WCs activated their muscles more effectively to reduce drag during leg recovery and had a quicker transition from plantarflexion to dorsiflexion. That could also be a reason why they spent less time in this phase. In contrast to the six other participants, the two world champions showed no coactivation in gastrocnemius and tibialis anterior during the complete stroke cycle. This indicated a better movement economy between dorsi- and plantarflexion of the ankle to generate propulsion and reduce drag. This is in accordance with studies conducted in running,[17,19] where it was found that excessive coactivation was an inefficient process that increased the metabolic cost.

Biceps femoris (long head) and rectus femoris

All of the swimmers showed coactivation in biceps and rectus femoris during the leg propulsion phase, indicating that knee extension was generated with high power. High angular velocities for the knee during this phase in breaststroke corresponded to a powerful extension[15] and could be considered a strategy for better controlling the precision and safety of the movement.

All of the WCs, but only one NE showed activation in rectus femoris during the beginning of the leg glide phase. This showed that full knee extension occured after the completion of the insweep of the legs for WCs as previously identified.[14] For the WCs this might point to an active strategy in performing an undulation with the hip slightly flexed and with the buttocks lifted up towards the water surface which was evident in the motion capture.

The WC swimmers spent a shorter time in the leg recovery phase compared to NE swimmers, similar to published results.[31] This may be because WCs showed longer activation in biceps femoris during this phase compared to NEs. This indicated that WCs used biceps femoris more actively to bring the heels up to the buttocks for a quicker leg recovery, as previously indicated,[14] to ensure minimum forward flexion of the thigh to keep water resistance to a minimum.

Trapezius (pars descendens) and pectoralis major (pars clavicularis)

Of the eight muscles tested, all swimmers showed the longest periods of activation for trapezius and pectoralis major relative to the stroke cycle. Six of the swimmers, including both world champions, had trapezius activated throughout the leg propulsion phase. Therefore suggesting that trapezius was activated to maintain upper body streamline position during this phase. In addition WCs had more activation in both pectoralis major and trapezius for this phase than NEs. This revealed that WCs might further optimize and lengthen the upper body streamlined position.

The hand in-sweep is often the most propulsive phase of the arm stroke.[32] This can be linked to the activation in pectoralis major, which is a powerful muscle that generates forward propulsion from the upper limb. A large difference between the two world champions and the other swimmers was seen during the propulsive arm pull (leg glide phase) for the pectoralis major. The two world champions activated their pectoralis major longer than the other swimmers during this phase. In addition, three of the NEs did not start activating pectoralis major until the last 25% of this phase. This implies that the world champions were able to "grab" the water earlier and generated higher forward propulsion from the arm pull while the legs glided. It also indicated that they used a more continuous coordination mode as identified when comparing the glide and continuous stroke.[29]

Practical applications

The practical implications of the findings in this study may contribute to enhanced performance in today's upcoming breaststroke swimmers. This suggests that coaches and swimmers could focus on the following points when evaluating breaststroke technique:

- Avoidance of excessive use of the triceps brachii during the leg propulsion phase which may cause an earlier onset of muscular fatigue.
- An early activation in the biceps brachii during the leg glide phase for elbow flexion to generate earlier arm propulsion.
- An active use of the gastrocnemius during this phase to improve streamlined position of the feet.
- A late and quick activation in the tibialis anterior during the leg recovery phase for reducing drag.
- Avoidance of excessive coactivation in the tibialis anterior and gastrocnemius during the stroke cycle, which may cause an earlier onset of muscular fatigue.
- Activation in the rectus femoris at the beginning of the leg glide phase for a full knee extension after the feet insweep.
- An early activation in the biceps femoris during the leg recovery phase to decrease the time spent.
- Activation in the trapezius during the leg propulsion phase for maintaining upper body streamline.
- An earlier and longer pectoralis major activation during the leg glide phase for generating higher forward propulsion from the arm pull.

However, such feedback about muscle activation might be difficult to interpret and apply during swimming. Using training exercises that focus on emphasizing the optimal recruitment pattern of agonist and antagonist muscles and the correct timing might be easier to apply. Therefore, future research should consider investigate the common techniques and drill exercises currently employed by coaches and swimmers to investigate which of these exercises develop and implement the correct muscular activation pattern in breaststroke technique. A future focus should also be placed on dry-land exercises performed by the swimmers. For example, it is important to know which specific strength exercises on land would specifically develop and strengthen the correct muscular recruitment pattern for swimming breaststroke at the highest level.

Limitations of the study includes that 3D kinematics were only measured from cameras located underwater. This meant that markers on the upper body and arms went out of the water during certain parts of the stroke cycle. Surface EMG also has limitations and this is often related to deep tissue muscles, adipose tissue (fat) and crosstalk. Only superficial muscles can be measured with surface EMG. Higher adipose tissue leads to a decrease in the amplitude of the EMG signal, but was not measured in these swimmers. They were all at the elite level and it can therefore be expected that their adipose tissue is low and the impression was that the swimmers had a homogenous amount. Crosstalk occurs when the electrode receive signals from nearby muscles not being tested. This study tried to limit the crosstalk by ensuring appropriate electrode placements, but could not avoid sliding of the skin during the swimming. A limitation can also be that the swimmers performed one repetition of maximal effort. This was measured through Borg’s Rate of Perceived exertion, but a score of 19 or 20 after completion was homogeneously accepted as maximal effort. Finally, a limited sample size only allows limited conclusions to be reached.

Conclusion

In conclusion, this study revealed that distinct differences exist between WCs and NEs in terms of muscle activation patterns, coactivation and kinematic variables, which can help to provide swimmers’ performance discriminators. These findings may contribute to enhanced performance in today's breaststroke swimmers through the suggestions provided from this study regarding focus points when evaluating and training breaststroke technique.

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Table 1 Participant characteristics (means ± SD)

n	Sex	Age (yrs.)	Body mass (kg)	Height (cm)	Streamline height (cm)	FINA-points
2 World-class	Females	25.5 ± 4.0	66.2 ± 10.1	167.0 ± 1.4	213.0 ± 1.4	986.5 ± 10.6
2 World-class (world champions)	Males	27.3 ± 1.7	86.6 ± 0.8	188.0 ± 2.8	243.3 ± 1.1	1009.0 ± 22.6
2 National elite	Females	16.0 ± 1.9	63.9 ± 0.2	168.3 ± 6.0	210.5 ± 3.5	674.5 ± 29.0
2 National elite	Males	28.0 ± 12.1	83.1 ± 1.3	185.0 ± 2.8	235.8 ± 4.6	749.0 ± 4.2

FINA-points=the highest number of points for each swimmer, regardless of breaststroke distance or course.

Table 2a Time, length and velocity for the different phases and the total stroke cycle including stroke rate

Phase/Cycle	Time (s)	*p*-value	Length (m)	*p*-value	Velocity (m/s)	*p*-value	Stroke rate (strokes/min)	*p*-value
Leg propulsion								
World-class	0.37 (0.09)	.386	0.44 (0.23)	.773	1.25 (0.35)	.248		
National elite	0.42 (0.15)		0.46 (0.06)		1.08 (0.40)			
Leg glide								
World-class	0.64 (0.30)	.559	0.89 (0.36)	.248	1.42 (0.36)	.386		
National elite	0.60 (0.13)		0.81 (0.20)		1.24 (0.20)			
Leg recovery								
World-class	0.37 (0.09)	.043*	0.40 (0.13)	.248	1.03 (0.35)	.386		
National elite	0.46 (0.06)		0.47 (0.19)		0.99 (0.50)			
Total stroke cycle								
World-class			1.70 (0.30)	.564	1.30 (0.32)	.386	43.1 (9.9)	.248
National elite			1.65 (0.35)		1.12 (0.31)		40.9 (7.8)	

Values are median (interquartile range).
*Significantly different between world-class and national elite ($p < .05$).

Table 2b Knee angle at the beginning of each phase and the largest knee angle during leg glide

Knee angle (°)	Leg propulsion (°)	*p*-value	Leg glide (°)	*p*-value	Leg recovery (°)	*p*-value	Largest during leg glide (°)	*p*-value
World-class	41.7 (5.6)	.886	164.9 (19.2)	.486	155.5 (17.4)	.200	176.3 (10.0)	.886
National elite	42.4 (4.4)		173.2 (16.9)		161.9 (10.4)		177.0 (4.8)	

Values are median (interquartile range).
No significant differences were found between world-class and national elite ($p < .05$).

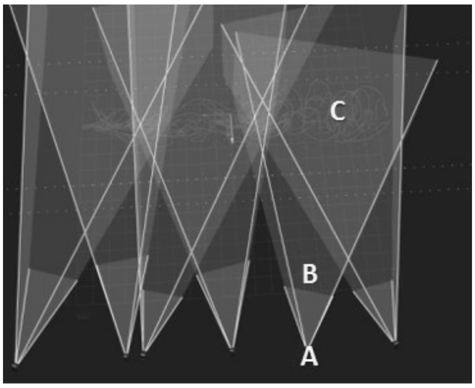

Figure 1 — 3D calibrated volume under water.
(A) placement of camera; (B) camera field-of-view (grey); and (C) calibrated volume.

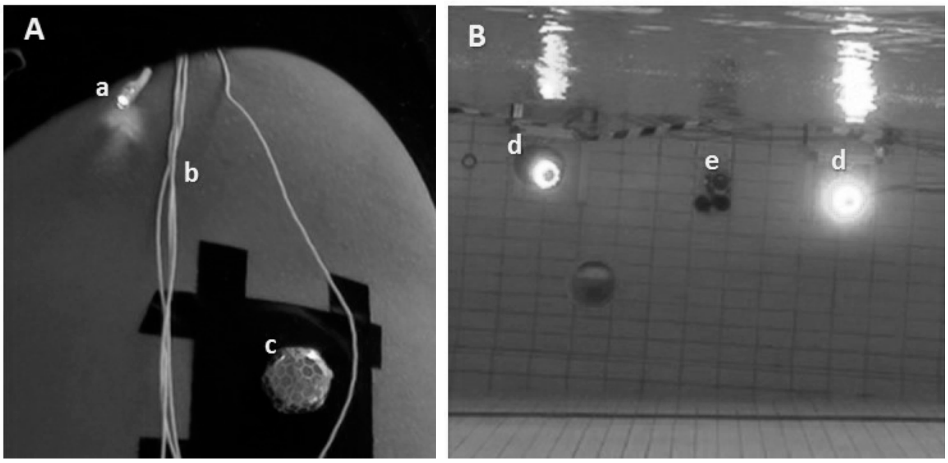

Figure 2 — Synchronization of the equipment through the view of the digital cameras (A); and (B).
(a) capturing the first blink of the EMG reference light; (b) cables (coming from the EMG sensors); (c) 3D marker attached to trochanter major with insulating tape; (d) capturing the first blink of the 3D cameras; and (e) one of the 2D cameras placed underwater for verifying the swimming movements in 2D.

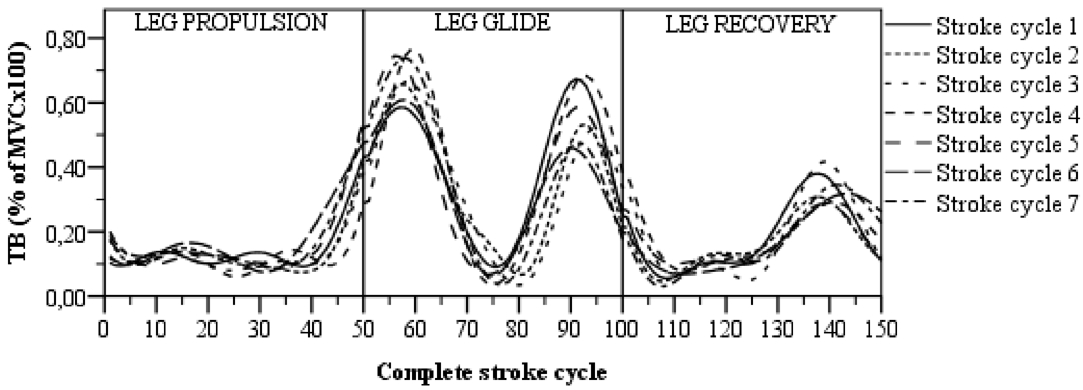

Figure 3 — Average muscle activation patterns from seven complete stroke cycles for the triceps brachii (lateral head) (TB) during maximal effort for a national elite swimmer. Amplitude was normalized to the relative maximal voluntary contraction (MVC) and time was normalized to the three stroke phases (50 points each).

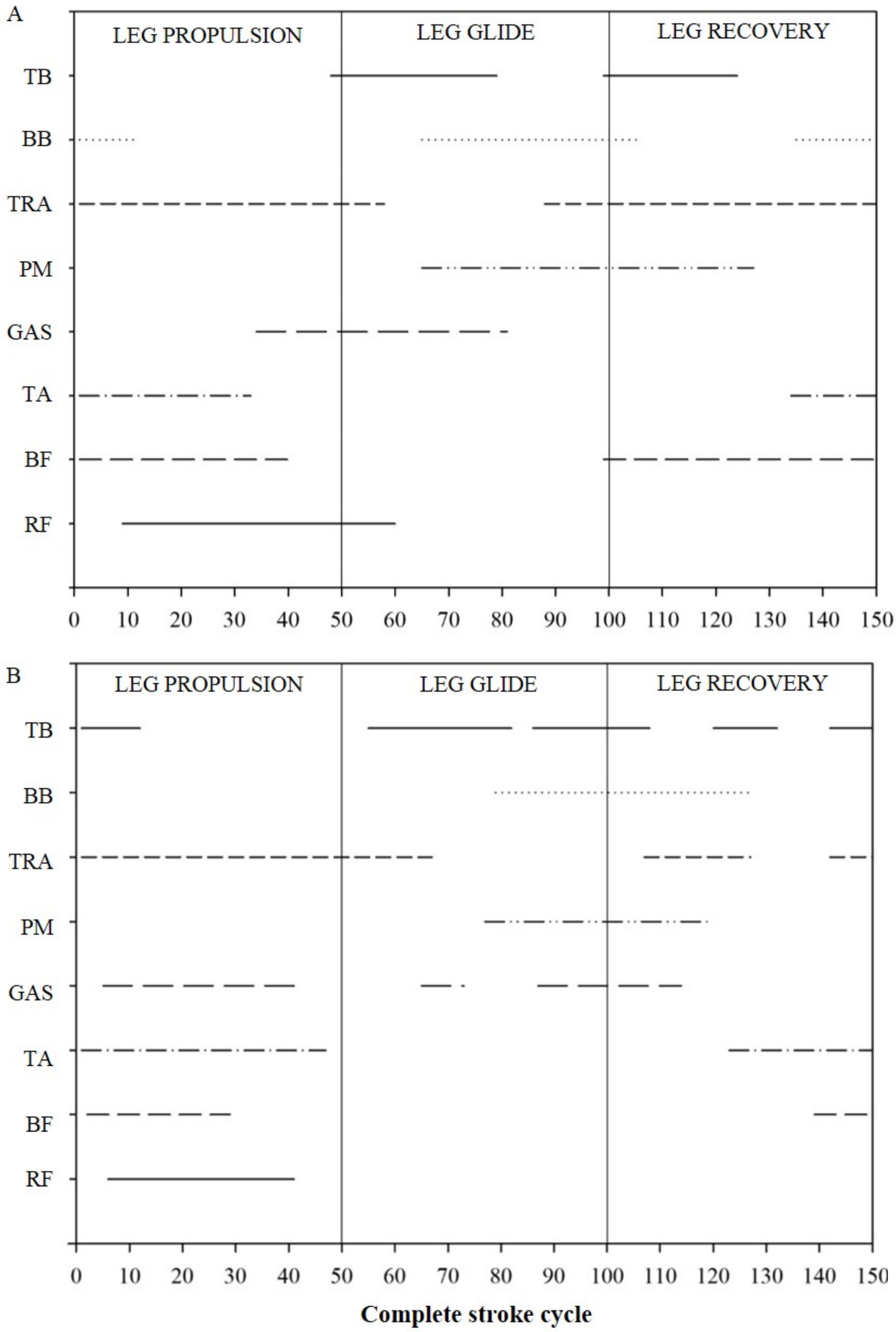

Figure 4 — An overview of the muscles activating during the different phases of the stroke cycle at maximal effort for (A) a world champion swimmer; and (B) a national elite swimmer. Time was normalized to 50 points for each of the three stroke phases compiling a complete stroke cycle. Muscles: TB = triceps brachii (lateral head); BB = biceps brachii (long head); TRA = trapezius (pars descendes); PM = pectoralis major (pars clavicularis); GAS = gastrocnemius (medialis); TA = tibialis anterior; BF = biceps femoris (long head); and RF = rectus femoris.

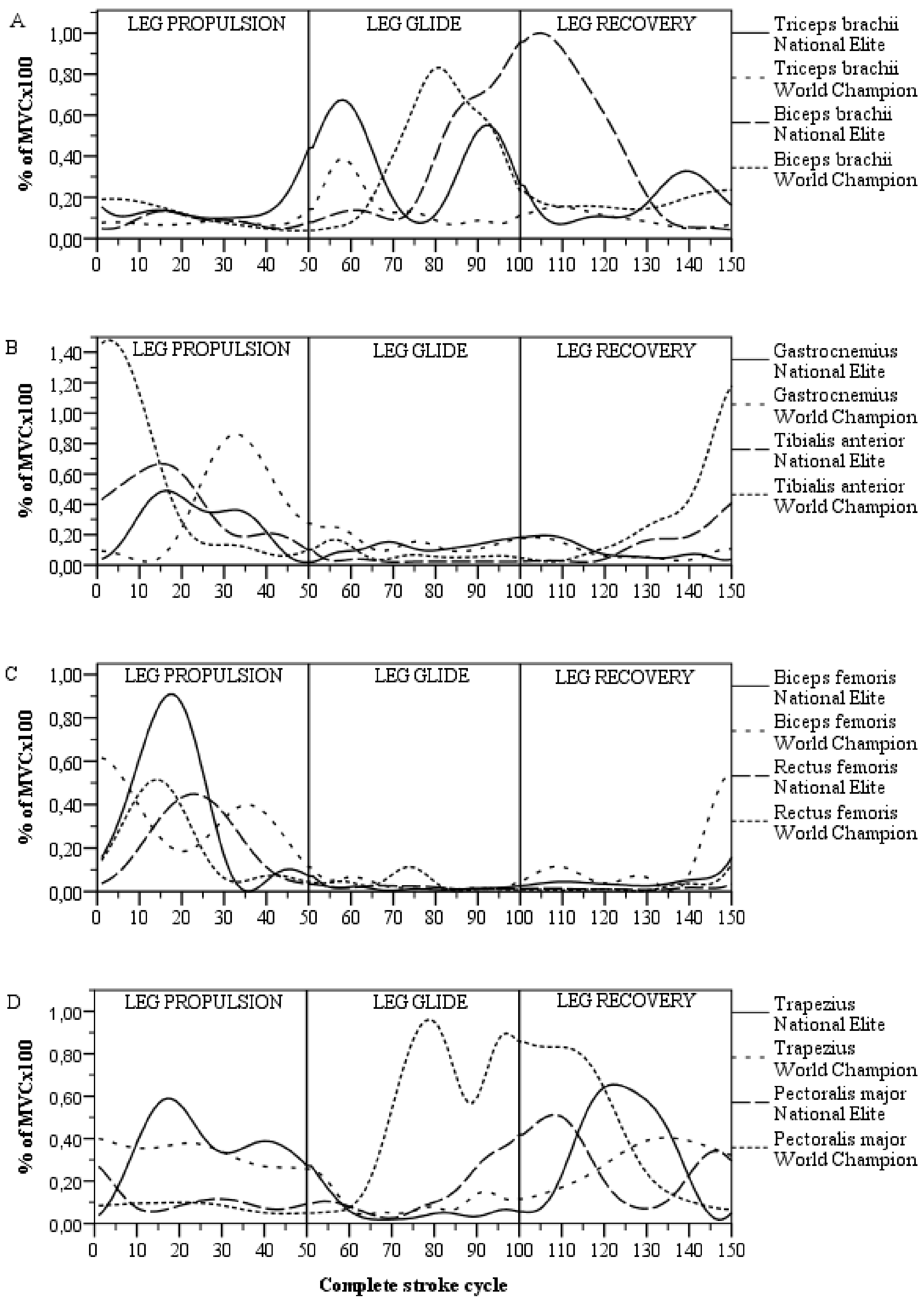

Figure 5 — Average muscle activation patterns for one national elite and one world champion swimmer during maximal effort. (A) triceps brachii (lateral head) and biceps brachii (long head); (B) gastrocnemius (medialis) and tibialis anterior; (C) biceps femoris (long head) and rectus femoris; and (D) trapezius (pars descendes) and pectoralis major (pars clavicularis). Amplitude was normalized to the relative maximal voluntary contraction (MVC) and time was normalized to 50 points for each of the three stroke phases compiling a complete stroke cycle.